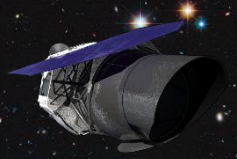
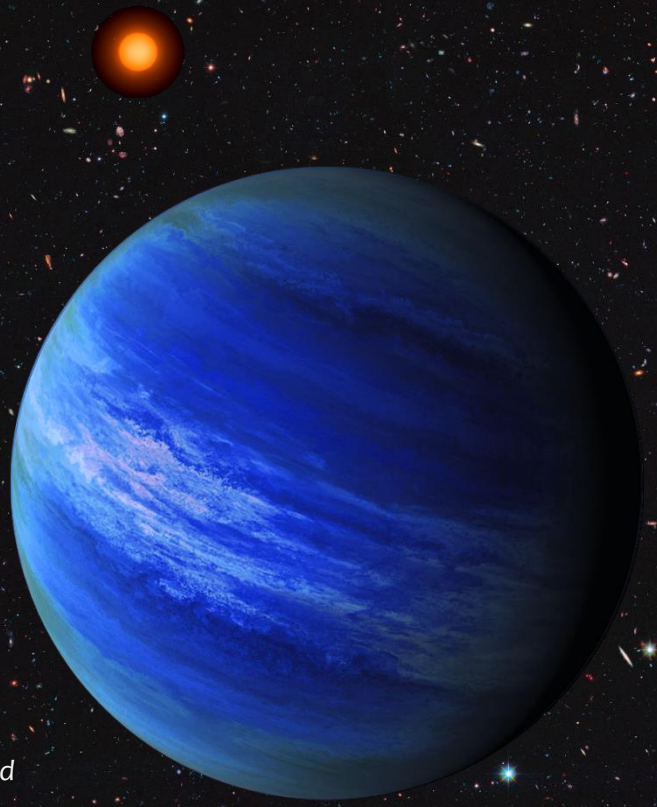
WFIRST SRR/MDR



Coronagraph Instrument



28 February 2018

Peg Frerking

Coronagraph Instrument Manager

Jet Propulsion Laboratory
California Institute of Technology

Agenda

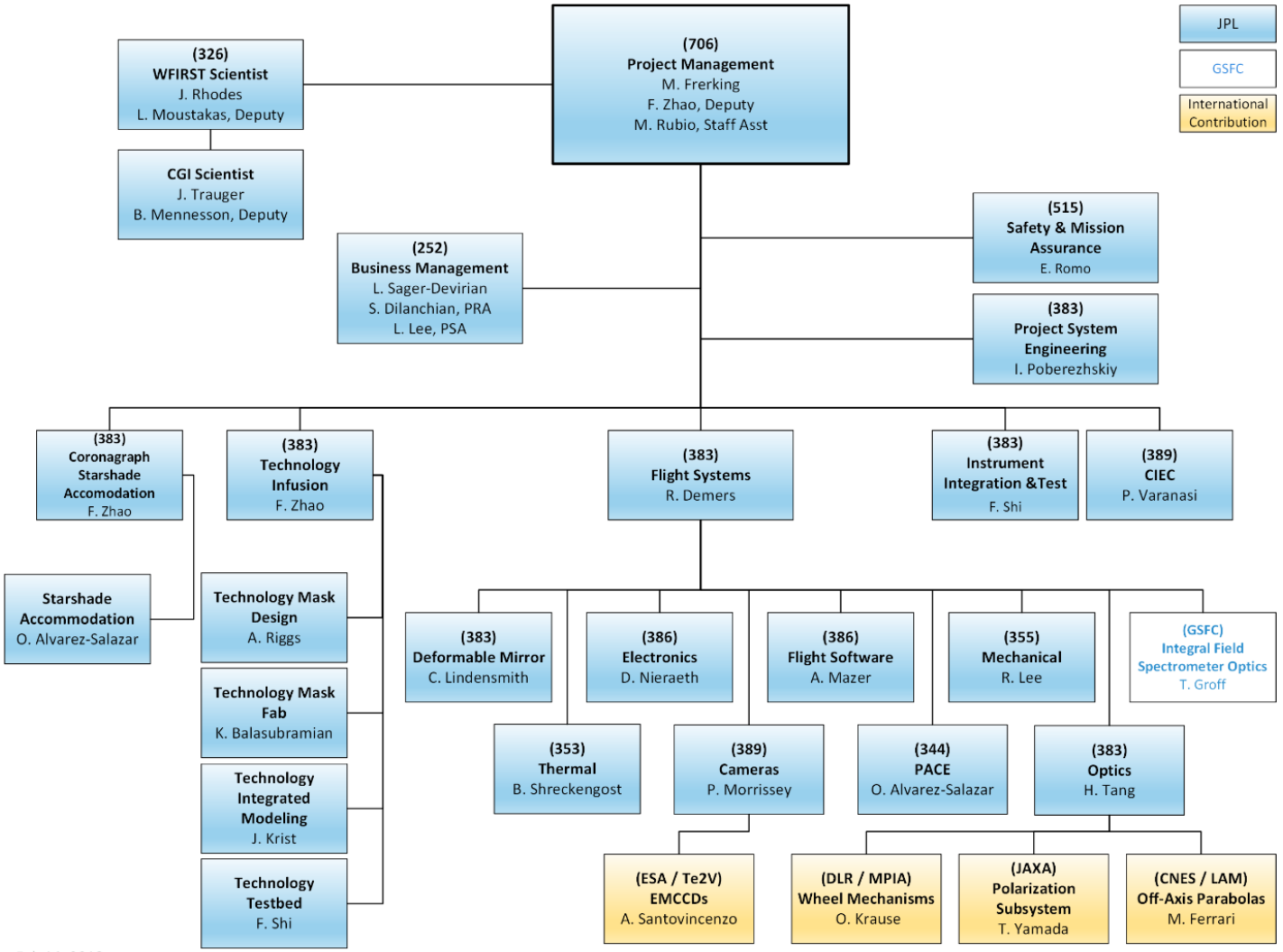
- Introduction
- Organization
- CGI Architecture
- CGI Concept of Operations
- CGI Design Concept
- Key and Driving Requirements
- Key Analysis
- Key Interfaces
- Key Technologies
  - TRL levels and development plans
  - Technology Infusion
- Schedule and Milestones
- Phase B Plans and Trades
- Summary

Introduction

- WFIRST Coronagraph Instrument (CGI) will demonstrate in space coronagraph technology required for characterization of rocky planets in the Habitable Zone, significantly reducing the risk for future Exo-Planet missions
  - High-Contrast Broadband Imaging
  - High-Contrast Imaging Spectroscopy
  - High-Contrast Extended Source Imaging and Polarimetry

- WFIRST CGI is
  - Technology Demonstration Instrument
  - Risk Class C
  - Implemented under NPR 7120.5e
  - Implemented by JPL, with significant partnership with other NASA centers, industry, academia and international institutions

CGI Organization Chart



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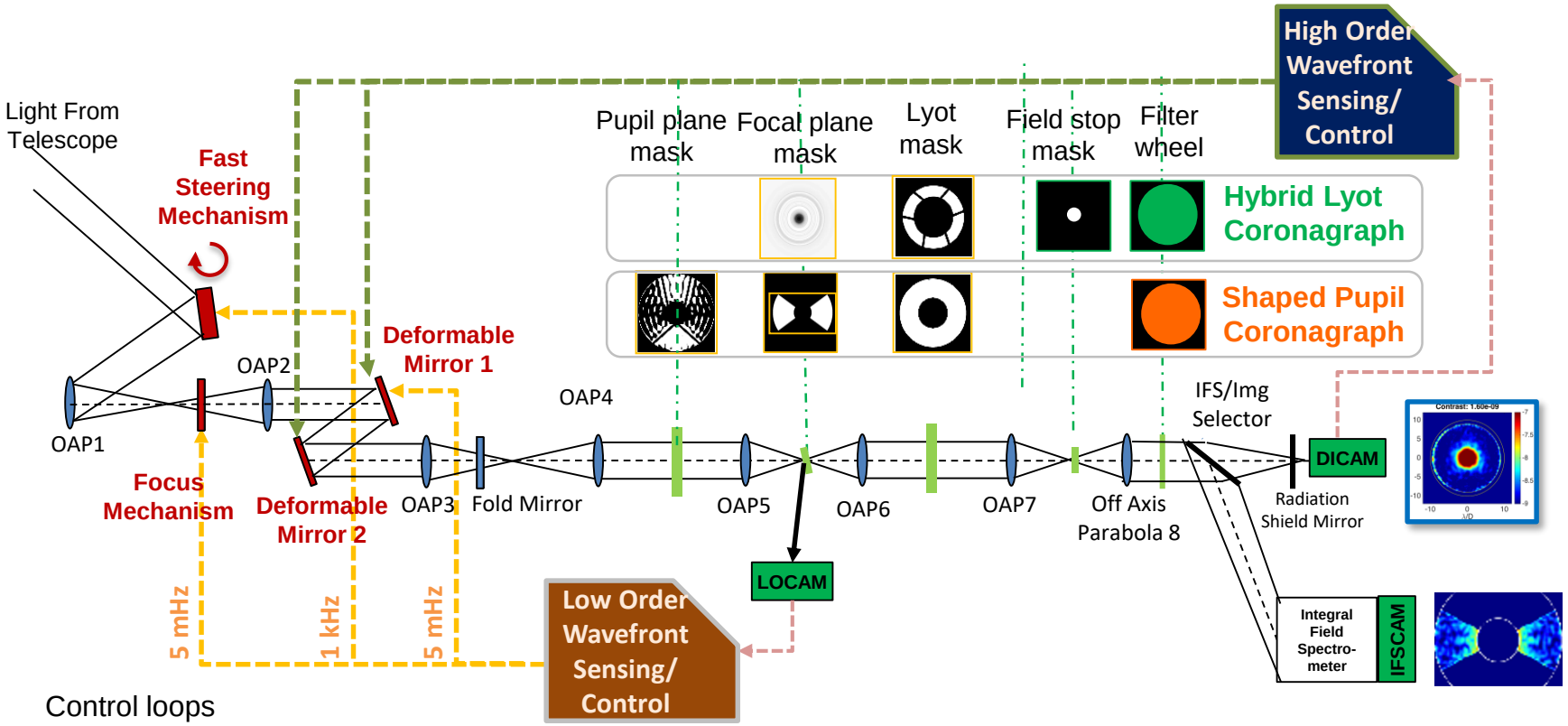
CGI Architecture



- Control loops
  - High order wavefront sensing control loop (HOWFS/C) for initially achieving starlight suppression
  - Low order wavefront sensing control loop (LOWFS/C) for continuously maintaining starlight suppression
- Active components
  - Fast Steering Mirror (FSM) for line of sight control
  - Focus Mechanism (FocM) for focus control
  - Deformable mirrors (DM1, DM2) for wavefront error control

CGI Concept of Operations

Acquire Reference Star
- Send CGI sensed error to observatory
- LOWFSC locks on star

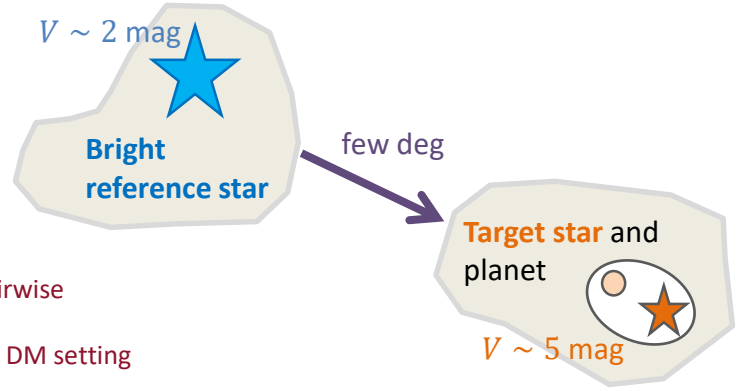
Precon-figure for Dark Hole
- Set masks, filter
- LOWFSC zeroes Tip/Tilt, focus, LOWFE

Generate Dark Hole
- Probes & pairwise estimation
- HOWFSC for DM setting

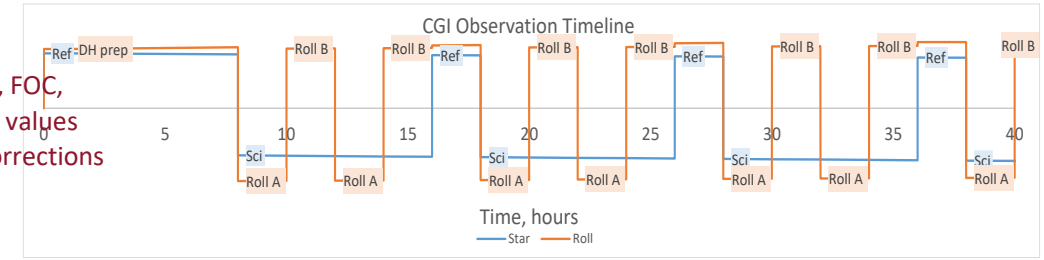
Acquire Target Star
- ACS move
- FocM, DM1,2 frozen

Observa-tion
- Set Tip/Tilt, FOC, DM1, DM2 values
- LOWFSC corrections

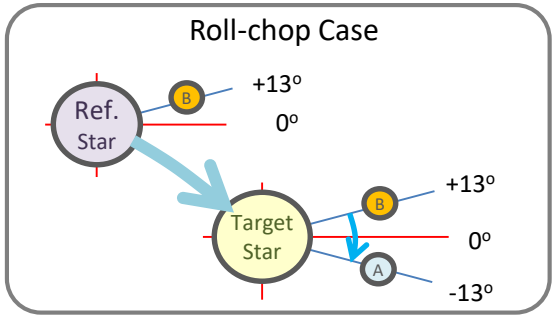
These steps are all conducted autonomously

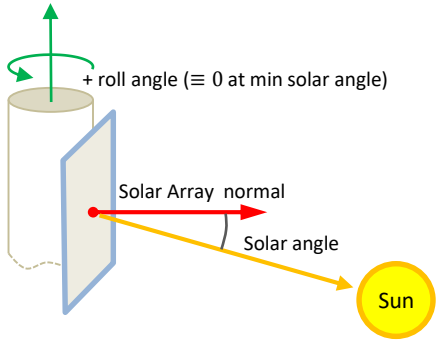


- CGI star-light suppression -*"dark hole"* - prepared while pointed at *reference* star.
- Use both roll-chop and star-chop to mitigate drift on long integrations.
- 2-hour cadence of roll-chop maneuvers on *target* star.
- 10-hour cadence of revisits to *reference* star.



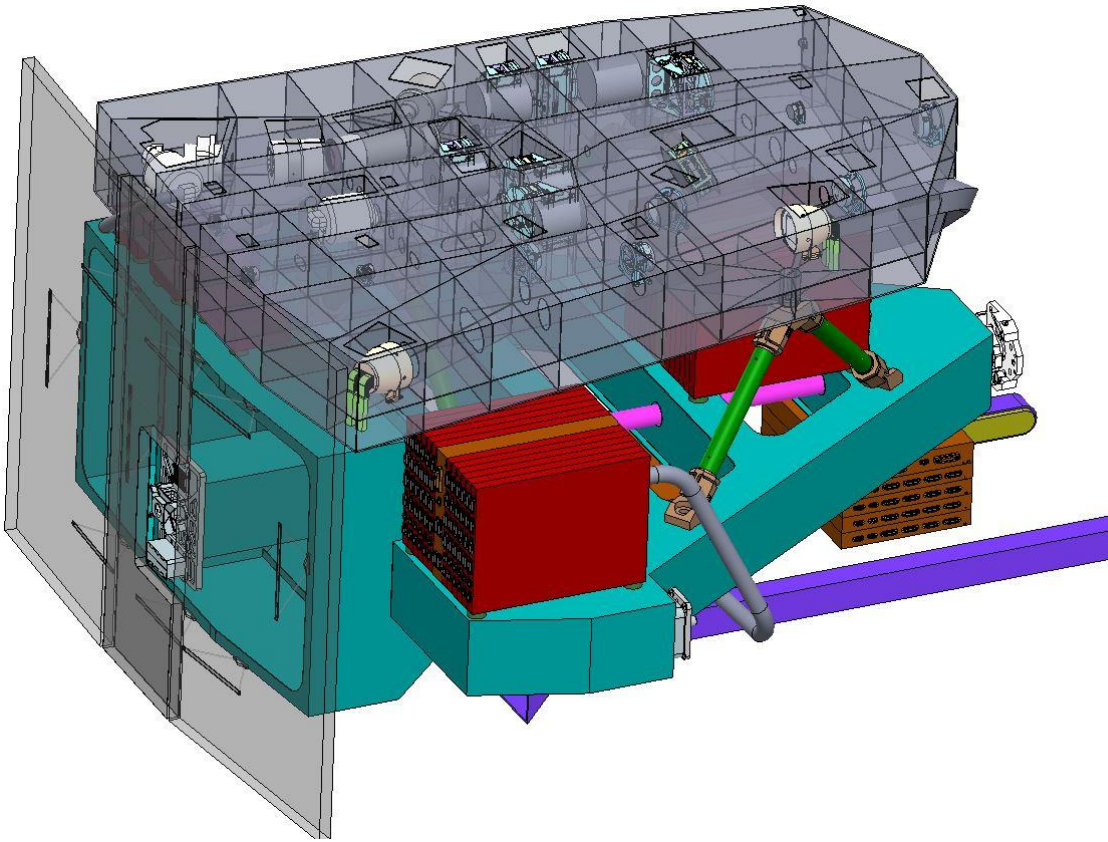
ACS	Attitude Control System
CGI	Coronagraph Instrument
DM	Deformable mirror
HOWFSC	High-order wavefront sensing & control
FocM	Focus Mechanism
LOWFSC	Low-order WFE sensing & control



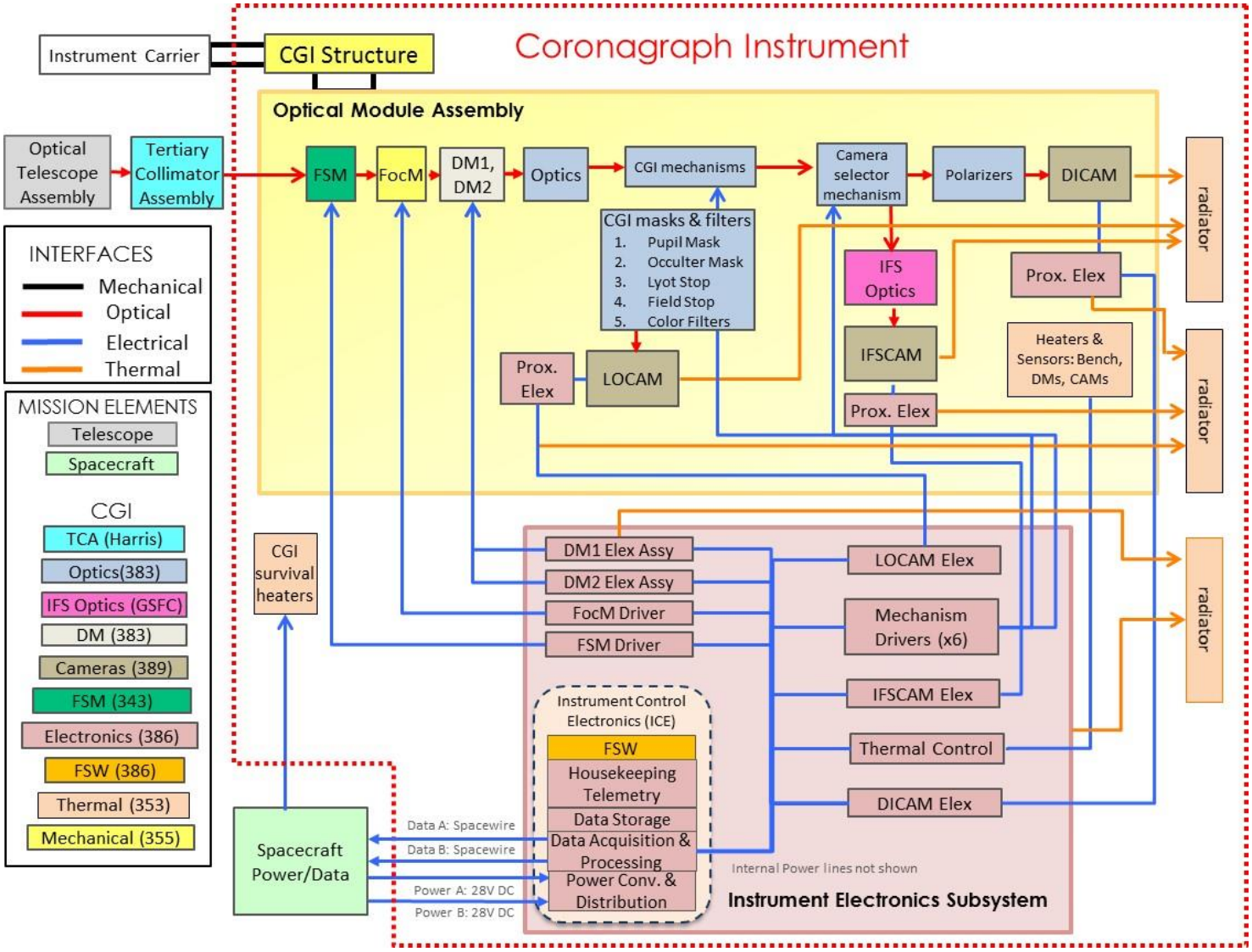


CGI Design Concept

- 2 PbMgNb Deformable Mirrors (48x48 actuators)
- Direct Imaging channel with Photon-Counting EMCCD passively cooled to 165 K
- Integral Field Spectrograph (R = 50, cooled EMCCD camera)
- Low-Order Wavefront Sensor (Rejected starlight, EMCCD camera)
- Active thermal control for bench, DM, and electronics
- Robotically serviceable payload interface
- Starshade accommodation



CGI Block Diagram



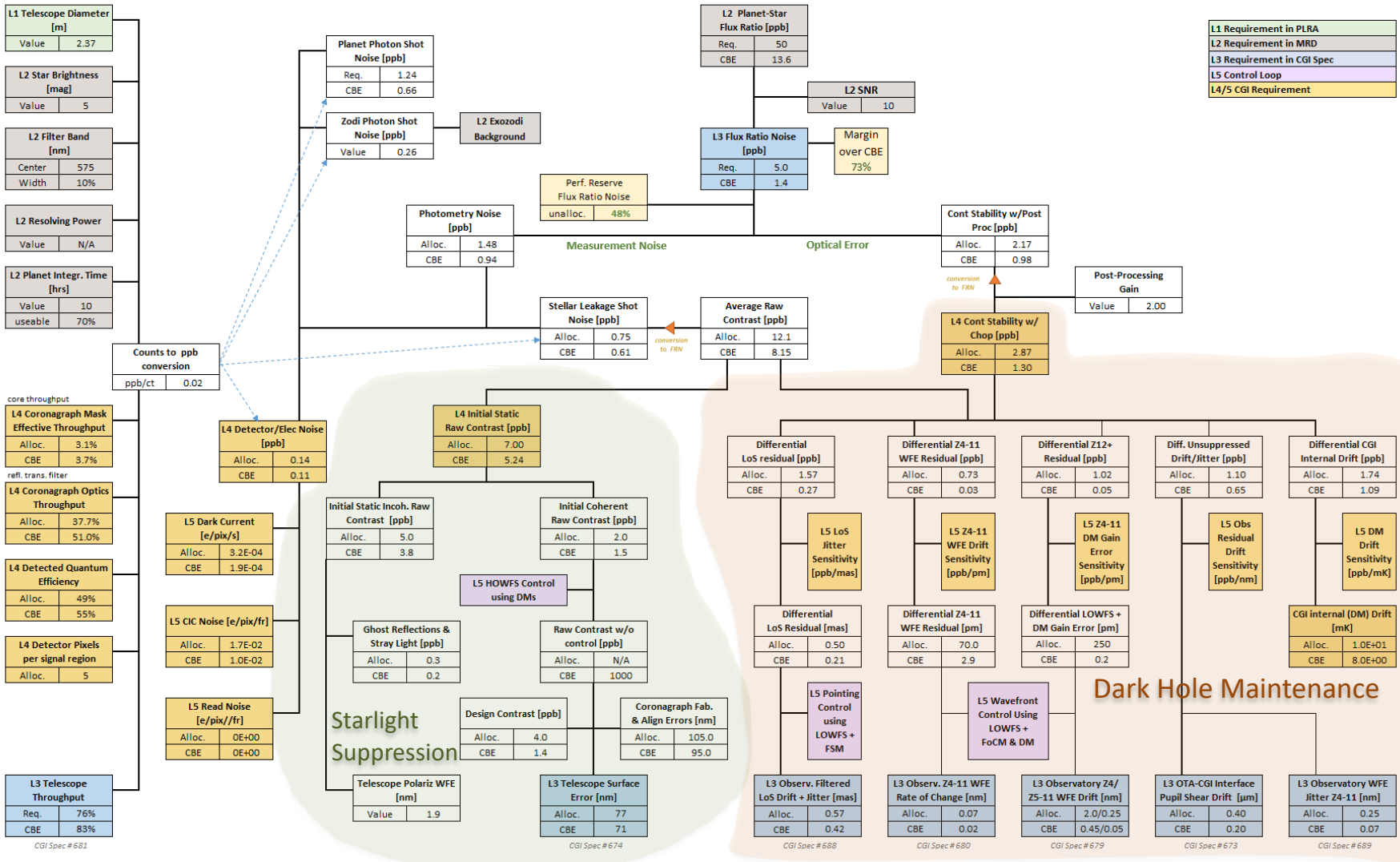
CGI is responsive to L2 MRD

	MRD #	L2 Description	CGI Spec #	L3 Description	L3 Req / CBE
CGI Accommodation	MRD-188	Coronagraph Instrument	all	WFIRST shall have a tech demo coronagraph w/ direct imaging & IFS	Yes / Yes
	MRD-189	CGI Optical Configuration	CGI-001, 666-686	CGI accommodates OTA collimated output	Yes / Yes
	MRD-202	Coronagraph Pointing & Stability Accuracy	CGI-601-606	Meet CGI pointing w/ ACS designed for WFI	Yes / Yes
	MRD-203	CGI Serviceability	CGI-005	CGI shall be serviceable	Yes / Yes
	MRD-204	Coronagraph Instrument Maximum High Rate Data Bus Data Volume	CGI-013	Maximum data rate to S/C over 24 hours	3 Tbit / 0.38 Tbit
CGI Performance	MRD-449	CGI Filter Bands	CGI-501	CGI shall carry the specified tech demo filter bands	4 / 4
	MRD-457	CGI Field of View	CGI-513	CGI field of view in DI channel	3 arcsec / 5 arcsec
	MRD-436	High Contrast Direct Imaging **driving**	CGI-505	Direct imaging flux ratio noise 3-9 λ/D	5e-9 / 1.4e-9 (4-8 λ/D)
	MRD-437	High Contrast Imaging Spectroscopy **driving**	CGI-506	IFS flux ratio noise 3-9 λ/D	5e-9 / 1.4e-9 (4-8 λ/D)
	MRD-438	Wavefront Control for Large Annular FoV	CGI-507	Direct imaging flux ratio noise 6-20 λ/D	5e-9 / 1e-9 (7-19 λ/D)
	MRD-451	Polarization of Disks, Linear Polarization Fraction Uncertainty	CGI-508, CGI-519	Measure degree of linear polarization of astrophys. source	0.03 / 0.01
	MRD-452	Exoplanet Astrometric Accuracy	CGI-515	Measure angular separation between off-axis sources and occulted star	5 mas / 4 mas
Obs. Characteriz.	MRD-453	WFS Telemetry	CGI-028	Download all telemetry to the ground, including LOWFS frames	Yes / Yes
	MRD-454	Telescope Polarization	CGI-508	Measurement in DI Channel with 4 linear polarizers	Yes / Yes
	MRD-455	Measure Pointing Jitter	CGI-509	Measure pointing jitter at CGI occulter	0.5 mas / 0.2 mas
	MRD-456	Measure Wavefront Aberrations	CGI-510	Measure optical wavefront (Z4-Z11) drift at CGI occulter	0.1 nm/hr / 0.01 nm/hr
SS Compatible	MRD-206	Starshade Science Filters	CGI-029	CGI shall carry starshade science filters	5 / 5
	MRD-207	Starshade Lateral Sensing	CGI-030	Implement lateral sensing algorithms developed by SS	Yes / Yes
	MRD-426	Scattered Light Protection	CGI-031	Detector performance protection from light scattered by starshade plumes	Yes / Yes

CGI Requirements Flow-down Example: MRD # 436 – High-Contrast Direct Imaging

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

CGI TOP LEVEL ERROR BUDGET | **DI HLC 575 nm REQ** | **Revision Date 2/15/2018**



CGI Key Analyses

- High Fidelity Error Budgets
  - Flux Ratio Noise
  - Initial Raw Contrast
  - Line of Sight Pointing
  - Optical Throughput
  - Deformable Mirror Stroke
  - Static Wavefront Error
  - Wavefront Error Drift


High Contrast Testbed

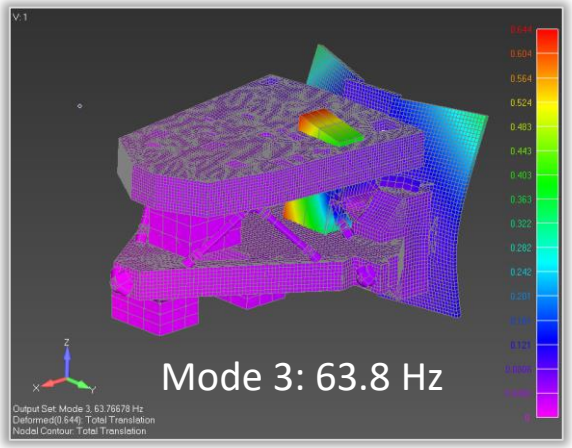
- Model Validation
  - Testbed validated model predictions for contrast to better than a factor of 2
  - Basis for setting Model Uncertainty Factor(MUF)

Configuration	Case	Testbed	Model	Difference
HLC, 550nm, 10% 3-9 λ/D	1	6.8E-09	4.6E-09	32%
	2	6.4E-10	7.5E-10	17%
SPC, 550nm, 10% 3-9 λ/D	1	2.0E-08	1.4E-08	30%
	2	4.0E-09	5.1E-09	28%

CGI Structural and Thermal Analysis

Structural FEM for Jitter & STOP Analysis

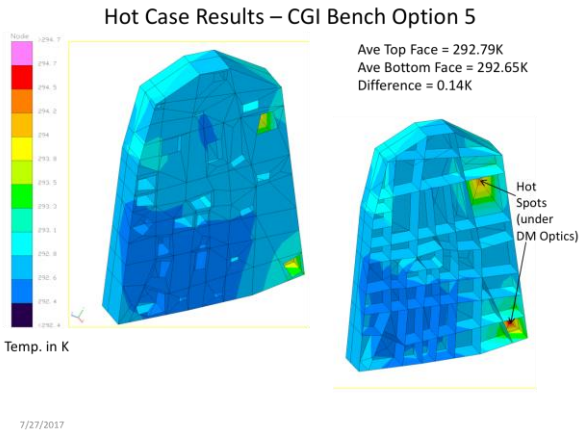
- Plate mesh for optical bench
- Lump masses to represent optical
- CTE for thermoelastic expansion included
- Modes analysis



Mode 3 is lowest mode with significant mass participation

Thermal Analysis

- 3 Radiators with heat straps/heat pipes
  - 3×EMCCDs
  - Proximity Electronics Boxes for three cameras
  - DM electronics & Instrument System Electronics
- Radiators individually sized to accommodate CBE+30%



CGI Key Interfaces

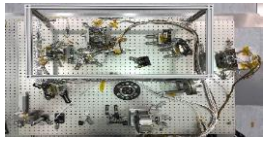
- Observatory – CGI Interface
  - Interface requirements have been agreed upon and captured in the CGI Specification
  - None drive the WFIRST design
    - Operational constraints during CGI observations, e.g. on reaction wheel speeds, may be used in the context of observatory designed to WFI requirements

CGI Spec #	Description	Req.	CBE
CGI Spec # 681	Telescope Optical Throughput (%)	76	83
Existing Capability	Telescope Polarization-Induced Wavefront Error (nm)	NA	1.9
CGI Spec # 674	Telescope Quasi-Static Wavefront Error (nm)	77	71
CGI Spec # 688	Observatory Filtered Line of Sight Drift + Jitter (mas)	0.57	0.42
CGI Spec # 680	Observatory Z4-11 Wavefront Error Rate of Change (nm)	0.07	0.02
CGI Spec # 679	Observatory Z4 / Z5-11 Wavefront Error Drift (nm)	2 / 0.25	0.45/ 0.05
CGI Spec # 673	Observatory OTA-CGI Interface Pupil Shear Drift (um)	0.4	0.2
CGI Spec # 689	Observatory Z4-11 Wavefront Error Jitter (nm)	0.25	0.07

CGI Key Technologies

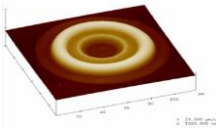
- Early (Pre-Phase A and Phase A) technology investment by NASA (SMD and STMD) to reduce risks to WFIRST mission
- All technology milestones for primary architecture were met on schedule and budget
- Only outstanding technology item is Deformable Mirror TRL 6

Autonomous Ultra-Precise Wavefront Sensing & Control System



First Use of PMN Deformable Mirrors in Space

High Contrast Coronagraph Masks



Ultra-low noise photon counting Visible Detectors

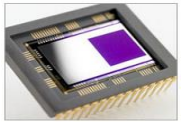
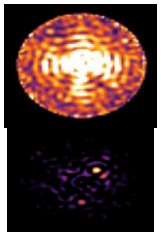


Image Processing at Unprecedented Contrast Levels

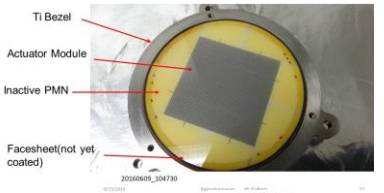


Deformable Mirror Maturation Plan

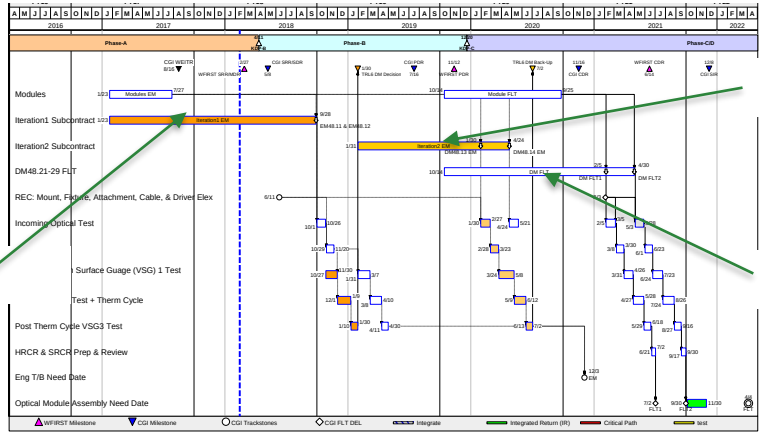
- State of the art: Prototype deformable mirrors with 48x48 actuators used in testbed with soldered pin grid array interconnect demonstrated all technology performance milestones very effectively.
- Pin grid array interconnect failed under thermal cycling due to the large CTE differences
- Contract on-going with AOA Xinetics to develop fuzz button interconnect.
  - Pressure contact rather than solder contact
  - Analysis shows compliance with environmental requirements
- Will complete environmental tests in late fall 2018.
- Plan includes a 2nd iteration of design prior to flight build.

Finished DM without Cover

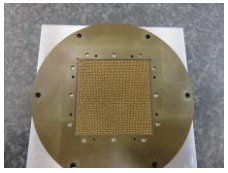
Actuator array

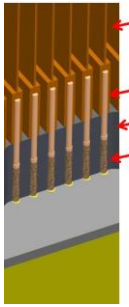


Blowup of Actuator array metallization



Fuzz Button array





Fuzz Button array cartoon

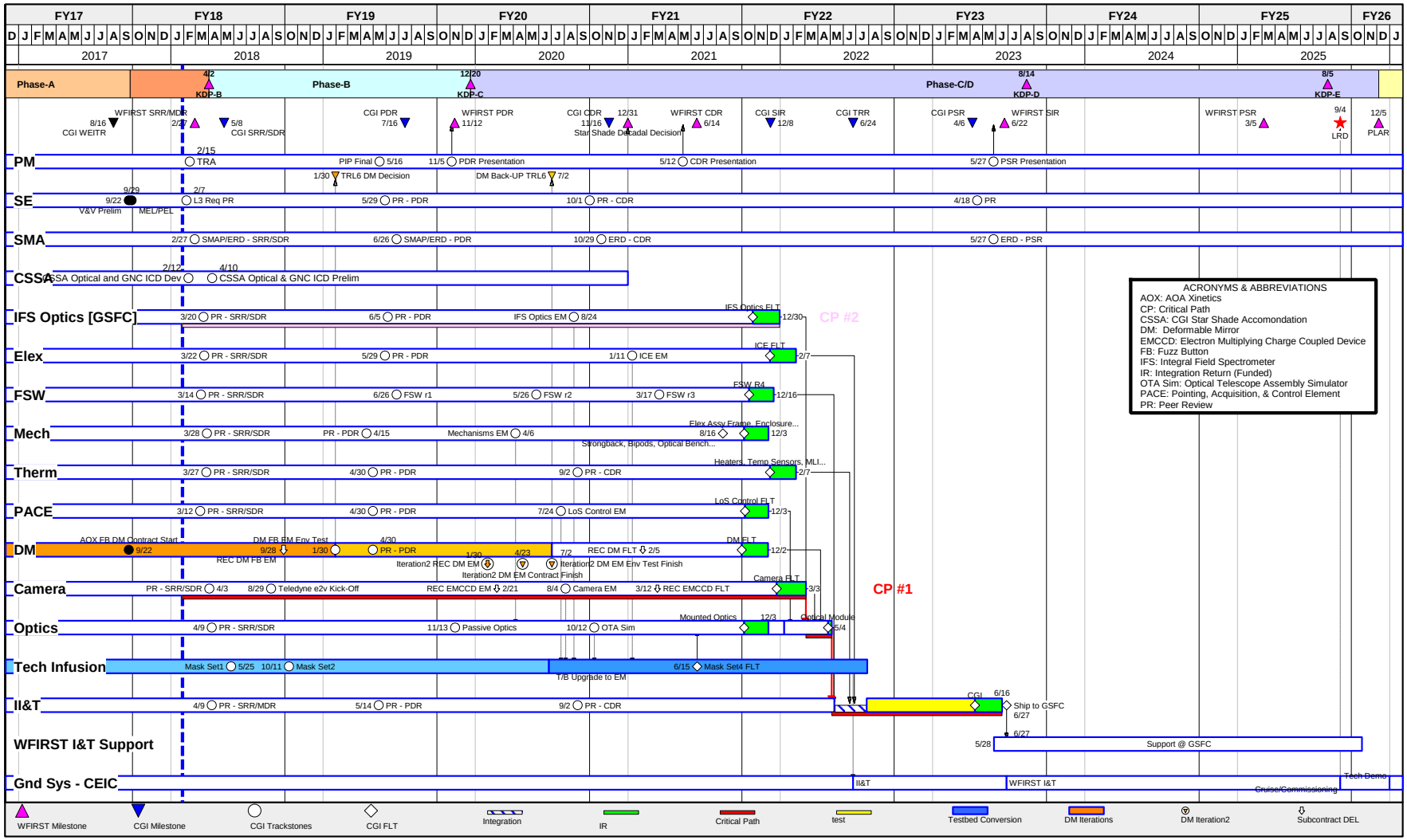
Technology Infusion

- Technology infusion
  - Planned performance improvement past CDR
  - Cost capped
- Technology infusion focus areas
  - Coronagraph masks
    - Continue to improve performance of coronagraph masks (throughput, bandwidth, sensitivity to interface)
    - Baseline mask implementation with 3 additional iterations
  - Control algorithms
    - Continue to improve efficiency for star suppression and contrast maintenance
- Enabled by high-fidelity testbed maintained throughout lifecycle
  - Technology development through CDR
  - Engineering validation up to delivery to WFIRST Integration and Test
  - Operations verification and validation to end-of-mission

CGI Schedule and Milestones

WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

1/28/18



Phase B Plans and Key Trades

- Develop preliminary design and refine operations concept
- Refine requirements and flowdown
- Bound risk on technology development and infusion
- Support project and instrument PDRs
- Baseline technical implementation and programmatic commitments

Design task/trade	Description
Flight Processor Architecture	Optimize use of flight processor elements to most efficiently perform on-board control algorithms
IFS to CGI bench mechanical interface	Aligned Sub-bench versus discrete sub-assemblies
DM 2nd iteration decision	PMN DM with fuzz button interconnect versus PMN DM with micro coil spring interconnect versus MEMs DM

Summary

- CGI performance requirements in place
  - Consistent with demonstrated testbed performance and validated model predictions
  - Healthy margin to protect from unknown-unknowns
- Key observatory interface requirements agreed upon
  - CGI does not drive mission design and schedule
- CGI team is ready to conduct preliminary design and Phase B activities